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Florian FIZAINE[a] and Victor COURT[b,c,d]

[a]Réseaux, Innovation, Territoires et Mondialisation (RITM), Univ. Paris-Sud, Université Paris-Saclay, 54, Boulevard Desgranges, 92330 Sceaux, France.

[b]*EconomiX, UMR 7235, COMUE Université Paris Lumières, Université Paris Ouest Nanterre La Défense, 200 avenue de la République, 92001 Nanterre, France.*

[c]*IFP Energies Nouvelles, 1-4 avenue du Bois Préau, 92852 Rueil-Malmaison, France.*

[d]*Chaire Economie du Climat, Palais Brongniart, 28 place de la Bourse, 75002 Paris, France.*

Abstract

We estimate energy expenditure for the US and world economies from 1850 to 2012. Periods of high energy expenditure relative to GDP (from 1850 to 1945), or spikes (1973–74 and 1978–79) are associated with low economic growth rates and periods of low or falling energy expenditure with high and rising economic growth rates (e.g. 1945–1973). Over the period 1960–2010 for which we have continuous year-to-year data for control variables (capital formation, population, and unemployment rate) we estimate that, statistically, in order to enjoy positive growth, the US economy cannot afford to spend more than 11% of its GDP on energy. Given the current energy intensity of the US economy, this translates in a minimum EROI of approximately 11:1 (or a maximum tolerable average price of energy of twice the current level). Granger tests consistently reveal a one way causality running from the level of energy expenditure (as a fraction of GDP) to economic growth in the US between 1960 and 2010. A coherent economic policy should be founded on improving net energy efficiency. This would yield a "double dividend": increased societal EROI (through decreased energy intensity of capital investment), and decreased sensitivity to energy price volatility.

Key words: energy expenditure, economic growth, energy prices, EROI.

JEL classification: N7, O1, O3, Q4, Q57.

E-mail adresses: florian.fizaine@gmail.com, vcourt@u-paris10.fr.

1. Introduction

Debate still continues about the relative contributions of production factors to economic growth. Georgescu-Roegen (1971, 1979) apart, economists have largely ignored the role of materials (e.g. metals) in the economic process. The attention paid to land vanished when modern industrial growth shifted the emphasis to capital availability. The importance of routine labor and human capital (knowledge, skills, etc.) has never been questioned, probably simply because economics is by essence the study of a human system in which humans *must* play the leading part. The role of energy in the economic process has come in for much discussion. In addition to the economic literature that we will investigate more specifically in the following subsections, the role of energy in society has been considered from sociological and anthropological (Podolinsky, 1880; Spencer, 1880; Ostwald, 1911; Soddy, 1926; White, 1943; Cottrell, 1955; Tainter, 1988), ecological (Lotka, 1922; Odum, 1971), and historical (Pomeranz, 2000; Kander et al., 2013; Wrigley, 2016) perspectives. The economic literature on the relationship between energy and economic growth splits into two[1] streams of research: (i) Mainstream econometric analyses of the relationship between energy price/quantity and economic growth; and (ii) the biophysical paradigm and its approach to the economic system through net energy and energy-return-on-investment (EROI).

1.1 The contribution of econometrics to the energy–economic growth relation

Energy prices and economic growth

Hamilton (1983) was the first of a score of studies concentrating on the relation between energy prices (usually the oil price) and economic growth (Katircioglu et al, 2015; Lardic and Mignon, 2008). Because the oil price impacts economic growth asymmetrically,[2] the classical methods of cointegration are ineffective, and more sophisticated methods are required to evaluate the energy price–economic growth relation (Lardic and Mignon, 2008; An et al., 2014). The scarcity of data on energy prices (across different countries and over time) complicates the assessment of this relation. In a nutshell, this literature seems to converge toward a feedback relation between variations in energy price and economic growth (Hanabusa, 2009; Jamil and Ahmad, 2010), ranging from a negative to a positive effect depending on the level of oil-dependency of the country under study (Katircioglu et al, 2015); and a clear negative inelastic impact of the oil price on GDP growth rates for net oil-importing countries. In addition, Naccache (2010) has shown that the impact of the energy price on economic growth depends on the origin of the oil price shock (supply, demand, or pure speculative shock), taking into account that the relative importance of each of these shock-drivers has varied considerably over time (Benhmad, 2013). When reviewing the literature, we found that all these studies consider that the oil price can exert a constant effect on an economy between two dates, whereas the energy intensity of this economy may obviously vary greatly over the same period of time. Just as the studies rightly assume that low- and high-energy intensive countries would not react in exactly the same way when confronted with

[1] In fact a third stream of research concerns theoretical economic models. We choose not to discuss this literature for the sake of space but one of the authors of the present paper has recently contributed to this field (see Court et al., 2016).

[2] The asymmetric response of the economy to the variation of the oil price can be explained by different factors such as the monetary policy, the existence of adjustment costs, the presence of uncertainty affecting investment choices and the asymmetric response of oil-based products to oil price variations. In the case of an oil price variation, the different adjustment costs may result from sector shifts, change in capital stock, coordination problems between firms, and uncertainty. When combined, these adjustment costs can completely erase the benefits associated with a fall in the oil price. See Lardic and Mignon (2008) and also Naccache (2010) for more information.

increased energy prices, (because the former are clearly less vulnerable), the same point should also be taken into account for a given country studied at different times. We therefore recommend explicitly introducing energy intensity as a key variable in future diachronic empirical assessments of energy price–economic growth relations.

Energy quantities and economic growth

Another impressive array of studies focuses on the relation between quantities of energy consumed and economic growth. Such studies have been conducted since the seminal paper of Kraft and Kraft (1978). From this energy quantity–economic growth nexus, four assumptions have been envisaged and systematically tested:

- A relation of cause-and-effect running from energy to economic growth. Studies supporting this assumption come close to the thinking of the biophysical movement (presented in the following subsection) and the proponents of the peak oil, because it gives a central role to energy in the economic process.
- A causal relation running from economic growth to energy. In this situation, energy is not essential and energy conservation policies can be pursued without fear of harming economic growth. This conservative view reflects the position of many neoclassical economists for whom energy is seen as a minor and easily substitutable production factor.
- A feedback hypothesis between energy and economic growth.
- The absence of any causal relation between energy and economic growth, which is also known as the neutrality assumption.

Unfortunately, after more than forty years of research and despite the increasing sophistication of econometric studies, this area of study has not so far led to either general methodological agreement or a preference for any of the four positions. More specifically, three independent literature reviews (Chen et al., 2012; Omri, 2014; Kalimeris et al., 2014), covering respectively 39, 48, and 158 studies, have shown that no particular consensus has emerged from this empirical literature and that the share of each assumption ranges from 20% to 30% of the total. Various explanations can be suggested for these mixed results, including the period under study, the countries in question (the level of development affecting the results), the level of disaggregation of the data (GDP or sectorial levels), the type of energy investigated (total energy, oil, renewable, nuclear, primary vs. final energy, exergy, etc.), the econometric method applied (OLS, cointegration framework, VAR, VECM, time series, panel or cross-sectional analysis), the type of causality tests (Granger, Sims, Toda and Yamamoto, or Pedroni tests), and the number of variables included in the model (uni-, bi-, or multivariate model) (Kocaaslan, 2013; Huang et al, 2008a,b; Wandji, 2013).

1.2 Biophysical economics and energy expenditure

Biophysical economics

Despite this lack of consensus about the direction of econometric causality tests between energy price/quantity and economic growth, we do not think that the importance of energy in economics is invalidated. Suppose we try to determine the effect of energy consumption on the average speed of a car traveling between a series of equidistant refueling points. If we make a Granger causality test between the fuel bills obtained at each gasoline station (representing energy consumption) and the recorded average speed of the car (representing GDP growth), it would probably indicate a causal relation running from the latter to the former. Indeed, the higher the speed of the car, the higher the energy consumption (and the higher the gasoline bill). But no one can reasonably assume that energy does not play the primary role in propelling the car at some speed or other, and that we can cut energy consumption without affecting the car's motion. We believe this reasoning reinforces the third strand of thought about the energy–economic growth relation grouping the various lines of research in biophysical economics. Two pioneering researchers, Georgescu-Roegen (1971, 1979) and Odum (1971, 1973), respectively applied the laws of thermodynamics and energy accounting principles to the analysis of the economic system in the 1970s. Unfortunately, it was not these seminal studies that alerted economics scholars and public opinion to the dependence of modern economies on energy, but rather the tremendous negative impacts on economic growth of the two oil shocks of the same period. Even so, researchers in this field have pursued their efforts and produced very recent syntheses (Hall and Klitgaard, 2012; Ayres and Warr, 2009; Kümmel, 2011).

Energy expenditure as a limit to growth

As said previously, the two oil shocks of the 1970s were stark reminders of the world economy's dependence on fossil energy. Energy expenditure, also called energy cost, is the quantity of economic output that must be allocated to obtaining energy. It is usually expressed as a fraction of Gross Domestic Product (GDP). Murphy and Hall (2011a,b) suggest that "when energy prices increase, expenditures are re-allocated from areas that had previously added to GDP, mainly discretionary investment and consumption, towards simply paying for more expensive energy". These authors show graphically that, between 1970 and 2007, the economy of the United States of America (US) went into recession whenever the petroleum expenditure of the US economy exceeded 5.5% of its GDP. In addition, Lambert et al. (2014) suggest that in the US once energy expenditure rise above 10% of GDP recessions follow.

Bashmakov (2007) makes a difference between energy cost to GDP ratio and energy cost to final consumer income ratio. He identifies energy cost to GDP thresholds of 8–10% for the US (4–5% for final consumer income) and 9–11% for the OECD (4.5–5.5% for final consumer income) below which he finds almost no correlation between the burden of energy expenditure and GDP growth rates. However, when these thresholds are exceeded, the economy slows down and demand for energy falls until the energy cost to GDP/consumer income ratios are back below their thresholds. Bashmakov (2007) argues that until the ratio of energy expenditure to GDP reaches its upper critical threshold, it is all the other production factors that determine the rates of economic growth, and energy does not perform a "limit to growth" function. "But when energy costs to GDP ratio goes beyond the threshold, it eliminates the impact of factors contributing to the economic growth and slows it down, so the potential economic growth is not realized".

King et al. (2015b) estimate energy expenditures as a fraction of GDP for the period 1978–2010 for 44 countries representing 93–95% of the gross world product (GWP) and 73–79% of the IEA's listed world Total Primary Energy Supply (TPES) (>78% after 1994). The methodology used by these authors is set out in full in their article but it should be pointed out that they consider coal, oil, and natural gas for three sectors (industrial, residential, and electricity production), plus non-fossil (nuclear, renewable) electricity production for two sectors (industrial and residential). The quantities and prices of these different commodities were mostly retrieved from databases of the US Energy Information Administration (EIA). King et al. (2015b) aggregate these national energy costs to estimate the global level of energy expenditure from 1978 to 2010. They find that this estimated energy cost as a fraction of the GWP fell from a maximum of 10.3% in 1979 to 3.0% in 1998 before rising to 8.1% in 2008. King (2015) uses these data to perform simple econometric correlation (hence not causal) analyses that deliver the following main results: expenditure on energy expressed as a fraction of GDP is significantly negatively correlated with the one-year lag of the annual changes in both GDP and total factor productivity, but not with the zero-year lag of these same variables.

1.3 Missing perspective, goal, and content

As already stressed, the various energy expenditures estimated by King et al. (2015b) were only for the period 1978–2010, and the econometric analyses of King (2015) were not designed to infer any temporal causality between energy expenditure and economic growth, nor to estimate any potential threshold effect in such a relation. Consequently, we seek to achieve two related goals in the present paper. First, we think it is important to extend energy expenditure estimates (as fractions of GDP) to a larger time frame, for as many countries as possible.[3] In the present paper we are able to do this adequately for the US and the global economy from 1850 to 2012, and for the United Kingdom (UK) from 1300 to 2008.[4] Second, we wish to relate the level of energy expenditure as a fraction of GDP to the economic growth dynamics in order to quantitatively support the various qualitative results previously advanced by Murphy and Hall (2011a,b), Lambert et al. (2014), and King (2015). More precisely, focusing on the US due to the availability and consistency of data, we seek to:

- (i) Perform Granger causality tests to identify the direction of the possible causal relation between energy expenditure and GDP growth.
- (ii) Estimate the ultimate level of energy expenditure (as a fraction of GDP) above which economic growth statistically vanishes.
- (iii) Express this result in terms of the maximum average price of energy and the minimum societal energy-return-on-investment (EROI) that must prevail in the economy in order for economic growth to be positive.

The methodology used to estimate the level of energy expenditure as a fraction of GDP is developed in section 2. In that section we also present the different equations necessary to estimate the ultimate energy expenditure level above which economic growth statistically vanishes, and translate this result into the maximum tolerable energy price and minimum required EROI of society. We then succinctly present the logic of Granger causality tests. In section 3, we first show graphically our estimates of the level of energy expenditure as a fraction of GDP for the US and the world economy from 1850 to 2012. Then, we give, for the US only, our estimation of the ultimate level of total energy expenditure (as a fraction of GDP) above which economic growth seems statistically impossible. We then express this result as the maximum tolerable aggregated energy price (and oil price), or in other words, the minimum energy-return-on-investment (EROI), that the energy sector must have in order for the US economic growth to be positive. We then give the results of the various Granger causality tests for the restricted 1960–2010 period for which data are continuous and consistent. In section 4, we discuss our methodology and perform some sensitivity analysis of our results. We also compare our energy expenditure estimates for the US and world with the one for the UK calculated from 1300 to 2008 using data from Fouquet (2008, 2011, 2014). Finally, in section 5, we conclude and propose some research perspectives that would be worth investigating as an extension of the present work.

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[3] Fouquet (2011) highlights the danger of focusing on the price of energy rather than the price of energy services when considering the long-run because the former ignore major technological improvements. We completely agree with this statement and want to highlight that our work takes into account some of this technological progress through the energy intensity of the economy.

[4] Naturally, the geographical definition of the "United Kingdom" is quite blurred over such long time span (see Fouquet, 2008 for details).

2. Methods

2.1 Estimating energy expenditure

Equations and boundary

We note X_j the level of expenditure of a given energy *j* produced in quantity E_j and sold at price P_j in a given economy:

$$X_j \; = \; P_j E_j. \tag{1}$$

In our study, the *j* energy forms include the following marketed energy: coal, crude oil, natural gas, non-fossil electricity (i.e. nuclear and renewable electricity from hydro, wind, solar, geothermal, biomass and wastes, wave and tidal) and modern biofuels (ethanol and biodiesel). Hence, total expenditure of marketed energy, $X_{total\,marketed}$, is:

$$X_{total\,marketed} = \sum_j X_j = P_{average} E_{total\,marketed}. \tag{2}$$

With $P_{average}$ as the quantity-weighted average price of aggregated marketed energy:

$$P_{average} \; = \sum_j P_j \frac{E_j}{\sum_j E_j}, \tag{3}$$

and $E_{total\,marketed}$ the total supply of marketed energy:

$$E_{total\,marketed} \; = \sum_j E_j. \tag{4}$$

Usually, such estimates of marketed energy expenditure omit traditional biomass energy (woodfuel, crop residues[5]) because they usually represent non-marketed consumption for which average annual prices cannot be estimated. Consequently, if such an energy resource is omitted from equations (1) and (2), we necessarily underestimate contemporary levels of energy expenditure since woodfuel and crop residues still represent 70% of global renewable energy consumption nowadays (whereas hydro accounts for 20% and new renewable technologies such as wind power, solar PV, geothermal, wave, tidal, wastes, and modern biofuels account for the remaining 10%). But most importantly, for times prior to the 1940s when traditional biomass represented a large share of the total primary energy supply of many countries, we need a proxy for total energy expenditure including non-marketed energies in order to have a more accurate idea of the actual level of total energy expenditure. With E_{trad} as the quantity of traditional biomass energy, and $TPES = E_{total\,marketed} + E_{trad}$ as the total primary energy supply, we define, for a given economy, the proxy of total energy expenditure, $X_{total\,proxy}$, as:

$$X_{total\,proxy} \; = \frac{X_{total\,marketed}}{\left(1 - \frac{E_{trad}}{TPES}\right)}. \tag{5}$$

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[5] Formally, fodder supplied to draft animals should be added to traditional biomass energy estimates, but it is generally discarded due to difficulties of estimation. This is also the case for traditional windmills and water wheels.

In our results we will present a (second best) estimate of total energy expenditure for the US and world economy using the "total proxy method" in order to test its consistency with the (first best) estimate which includes woodfuel as marketed energy.

Data for the US

We used several sources summarized in Table 1 in order to estimate the prices of coal, crude oil, gas, electricity, woodfuel, and modern biofuels consumed in the US.

Table 1. Sources and original units of the different prices of energies consumed in the US.

Energy	Time and spatial coverage	Source	Original unit
Coal	1850-2012: US average anthracite price.	US Census Bureau (1975a, pp.207-209) from 1850 to 1948; EIA (2012, p.215) from 1949 to 2011; EIA (2013, p.54) for 2012.	Nominal $US/80-lb from 1800 to 1824; then nominal $US/short ton[6].
Oil	1861-1944: US average; 1945-1983: Arabian Light posted at Ras Tanura; 1984-2012: Brent dated.	British Petroleum (2015) for the entire period.	Nominal $US/barrel.
Gas	1890-2012: US average price at the wellhead.	US Census Bureau (1975a, pp.582-583) from 1890 to 1915; Manthy (1978, p.111) from 1916 to 1921; EIA (2016, p.145) from 1922 to 2012.	Nominal $US/thousand cubic feet.
Electricity	1907-2012: US average retail price.	US Census Bureau (1975b, p.827) from 1907 to 1959; EIA (2016, p.141) from 1960 to 2012.	Nominal $US cents/kWh.
Woodfuel	1850-2012: US average	Howard & Westby (2013, p.67); all commodities Warren & Pearson (1933, pp. 25-27); Manthy (1978, p.90).	Nominal $US/thousand board feet.
Biofuels	2000-2012: US ethanol (E85). 2002-2012: US biodiesel (B20).	US Department of Energy (2016)	Nominal $US/Gasoline Gallon Equivalent.[7]

In order to express all energy prices in the same convenient unit, i.e. International Geary-Khamis 1990 dollars[8] per terajoule (abbreviated $1990/TJ), we used the US Consumer Price Index of Officer and Williamson (2016) and different energy conversion factors from British Petroleum (2015) such as the average energy content of one barrel of crude oil (5.73E-03 TJ), the average energy content of one metric tonne of hard coal (29.5E-03 TJ), the average energy content of one thousand cubic feet of natural gas (1.05E-03 TJ), the average energy content of one gasoline gallon equivalent (1.2E-04 TJ), the average energy content of one thousand board feet of wood (2.3E-02 TJ), and the terajoule equivalent of one kWh (3.6E-06). We present in Figure 1 the resulting prices of coal, oil, gas, electricity, and woodfuel expressed in $1990/TJ (biofuels prices are omitted from this figure for the sake of clarity).

[6] 1 metric tonne = 1000 kg = 1.10231 short ton; 80-lb = 36.29 kg.

[7] 1 Gasoline Gallon Equivalent = 114,100 BTU.

[8] The International Geary–Khamis 1990 dollar (properly abbreviated Int. G-K. $1990), more commonly known as the international dollar, is a standardized and fictitious unit of currency that has the same purchasing power parity as the U.S. dollar had in the United States in 1990.

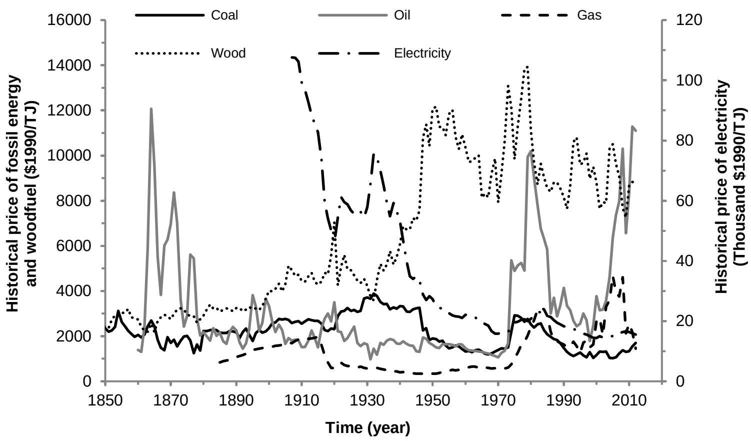

Figure 1. Estimations of US energy prices for coal (1850–2012, left scale), oil (1860–2012, left scale), gas (1890–2012, left scale), woodfuel (1850–2012, left scale) and electricity (1907–2012, right scale) in $1990/TJ.

US energy consumption levels were retrieved from EIA (2012, p.341) prior to 1950 and then EIA (2016, p.7) from 1949 to 2012. The nominal US GDP and deflator estimates were retrieved from Johnston and Williamson (2016) in continuous year-to-year time series from 1850 to 2012.

<u>Data for the World</u>

It is of course quite complicated to estimate the average annual price of a given energy type at the global scale. To be accurate in such estimations, one should formally have all national energy prices and consumption quantities and compute for each year a quantity-weighted average price of each energy. Given the broad time frame of our analysis, such estimation is simply impossible. Consequently, we will use the different energy prices estimated for the US as global proxies by considering that international markets are competitive and that large spreads between regional energy prices cannot last for long due to arbitrage opportunities. This assumption is fairly relevant for oil and gas. On the other hand, the hypothesis that the average international prices of coal, electricity, woodfuel, and modern biofuels follow their US equivalents is a rather coarse assumption. For instance, in the case of coal, transportation costs over long distances can be very high so that spreads between prices of two different exporting countries have necessarily occurred in the past. Furthermore, by using a single price for coal, we ignore the manifold qualities of coal (from the high energy content of anthracite to the lowest quality of lignite). As our coal price estimate is representative of anthracite, our coal expenditure estimates are probably high estimations of the actual levels of coal expenditure because we surely slightly overestimate the exact quality-weighted global average price of coal. Computing such a quality-weighted global average price of coal would be possible if we knew both the proportions of all the different coal qualities in the total global coal production (i.e. the quality mix of the global coal supply) and their respective prices, for each year between 1850 and 2012. As far as we know, such data is unfortunately not available.

We retrieved global primary energy productions through the online data portal of The Shift Project (2015) which is built on the original work of Etemad and Luciani (1991) for 1900–1980 and EIA (2014) for 1981–2012. Prior to 1900, we completed the different fossil fuel time series with the original five-year interval data of Etemad and Luciani (1991) and filled the gaps by linear interpolation. The work of Fernandes et al. (2007) and Smil (2010) was used to retrieve historical global consumption of traditional biomass energy (including woodfuel and crop residues but excluding fodder and traditional windmills and water wheels). The gross world product (GWP) we used comes from Maddison (2007) for 1850 to 1950 and from the GWP per capita of The Maddison Project (2013) multiplied by the United Nations (2015) estimates of the global population for 1950 to 2010. In order to obtain GWP estimates for 2011 and 2012 we used the real GWP growth rate of the World Bank (2016a).

2.2 Estimating the maximum level of energy expenditure, the maximum tolerable price of energy, and the minimum EROI of society

In this section we present the methodology used to estimate the maximum level of energy expenditure above which economic growth cannot be positive. Then, we show how to translate this result into the maximum tolerable price of energy, or in other words, the minimum EROI of society. Although we are pretty confident in using US energy prices as global proxies for estimating the global level of energy expenditure, the following equations and econometric tests will only be applied to the US due to the lack of availability, consistency, and confidence that we have in global estimates of population and capital formation (as a fraction of GWP). Indeed, continuous population estimates are readily available for the US for the entire period of study of this article, whereas continuous estimates of global population are only available since 1950. Regarding gross capital formation as a fraction of GDP, the World Bank (2016b) proposes estimates from 1960 to 2013 for the US, but only from 1970 to 2013 for the global economy. Moreover, confidence in data is logically higher for a well-administered nation like the US than for global estimates.

<u>Multivariate linear regressions of economic growth on energy expenditure, capital formation, and labor availability</u>

In the US case, once total expenditure of marketed energy ($X_{total\,marketed}$) is computed, we can perform different multivariate linear regressions. The US GDP growth rate (obtained from Johnston and Williamson, 2016) representing the dependent variable can be regressed on several explanatory variables, namely: energy expenditure as a fraction of GDP (in which all marketed energy forms can be considered, or just a subset such as oil), capital formation as a fraction of GDP (retrieved from the World Bank, 2016b), and the US population (from Johnston and Williamson, 2016). As we suspect population to be a poor proxy for labor availability, we will also test in our regressions the explanatory power of the US unemployment rate (provided by the Bureau of Labor Statistics, 2016). The general formula of the multivariate linear regression we study is:

$$\frac{G\dot{D}P}{GDP} = \alpha + \theta_1 \frac{X_{total\,marketed}}{GDP} + \theta_2 \frac{Capital\,formation}{GDP} + \theta_3 \Delta Population. \tag{6}$$

Where $\frac{G\dot{D}P}{GDP}$ is the US economic growth rate, α is the intercept, θ_1 (for which we logically anticipate a negative value) represents the sensitivity of the economic growth rate to the level of energy expenditure as a fraction of GDP, θ_2 is the sensitivity of the economic growth rate to the capital formation as a fraction of GDP, and θ_3 is the sensitivity of the economic growth rate to population first difference $\Delta Population$. It is important to point out that the main advantage of our approach is that it takes into account both the impact of energy prices and energy efficiency on economic growth. Indeed, it should be remembered that energy expenditure as a fraction of GDP can be broken down as the average price of energy times the energy intensity (inverse of energy efficiency) of the economy:

$$\frac{X_{total\,marketed}}{GDP} = \frac{\sum_j P_j E_j}{GDP} = P_{average} \times \frac{\sum_j E_j}{GDP} = P_{average} EI. \quad (7)$$

Where EI is the energy intensity of the economy. So, rather than considering only the impact of energy price or energy quantity fluctuations on economic growth, as is usually done in econometric studies, we suppose here that energy prices impact the economy variously depending on the energy efficiency of the economy. The higher the energy intensity of the economy, the higher the negative impact of energy price increases.

Maximum tolerable level of energy expenditure

Using equation (6), it is easy to find the particular value of US energy expenditure (as a fraction of GDP) that leads to zero economic growth. In other words, we can define the maximum level of energy expenditure (as a fraction of GDP) above which positive economic growth is impossible. We call β_{total} this maximum level of energy expenditure, with:

$$\beta_{total} = \left(\frac{X_{total\,marketed}}{GDP}\right)_{max} = \frac{-\alpha - \theta_2 \frac{Capital\,formation}{GDP} - \theta_3 \Delta Population}{\theta_1}. \quad (8)$$

Maximum tolerable quantity-weighted average price of energy

Defining the maximum level of energy expenditure above which positive economic growth is impossible can be reformulated as the maximum aggregated price of marketed energy $P_{average\,max}$ that the economy can tolerate to still present a slightly positive growth rate. Of course, this hypothetical maximum tolerable price of aggregated energy depends on the energy intensity of the US economy as shown in (9):

$$P_{average\,max} = \frac{\beta_{total}}{\frac{E_{total\,marketed}}{GDP}}. \quad (9)$$

Minimum EROI required to enjoy positive economic growth

Considerable research has been conducted into the concept of energy-return-on-investment (EROI) of human societies since all organisms or systems need to procure at least as much energy as they consume in order to continue in existence. The EROI is the ratio of the quantity of energy delivered by a given process to the quantity of energy consumed in that same process. Hence, the EROI is a measure of the accessibility of a resource, meaning that the higher the EROI, the greater the amount of net energy delivered to society in order to support economic growth (Hall et al., 2014). King et al. (2015a) point out that this definition is rather loose and that a clear distinction should be made between yearly "power return ratios" (PRRs) of annual energy flows and "energy return ratios" (ERRs) of full life cycle energy systems (i.e. cumulated energy production divided by total lifetime invested energy) which more formally represent EROIs. Understandably, energy return ratios represent integrals of power return ratios over the entire life cycle of the energy system under consideration.

Following King and Hall (2011), an estimate of the yearly or "instantaneous" EROI of a given economy (taking into account only marketed energies for which prices are available) can be expressed as a function of the quantity-weighted average price of aggregated marketed energy, $P_{average}$, the average monetary-return-on-investment (MROI) of the energy sector (i.e. its gross margin), the gross domestic product (GDP), and the total supply of marketed energy $E_{total\,marketed}$:

$$EROI = \frac{MROI}{P_{average} \times \frac{E_{total\,marketed}}{GWP}}. \tag{10}$$

If we replace $P_{average}$ in (10) by the expression (9) of $P_{average\,max}$, we obtain an expression of the $EROI_{min}$, which is the minimum societal EROI that the energy system must have in order for the economy to enjoy a positive rate of growth:

$$EROI_{min} = \frac{MROI}{\beta_{total}}. \tag{11}$$

Robustness of econometric regressions and auxiliary tests

All of our estimations were preceded by unit root tests in order to check the stationarity of our time series and avoid spurious regressions. For the various estimations of energy expenditure, the Augmented Dickey Fuller test (ADF) provides conflicting results with the KPSS test. When we observe the residuals of the auxiliary regressions of ADF, it seems that the outcome of the test is biased by two important outliers occurring in 1974 and 1979 (years of oil shocks). If we introduce two dummy variables to capture this effect, or if we start the test after the oil shocks, the ADF test indicates that the various estimations of energy expenditure as a fraction of GDP are stationary. Except for the US population, the tests indicate that all other variables (US GDP growth rate, US capital formation as a fraction of GDP, and US unemployment rate) are stationary. To save space, outcomes for unit root tests are reported in the Appendix.

Concerning econometric regressions, we report systematically different tests for the residuals of the estimations, especially tests of autocorrelation (Durbin-Watson [9]), homoscedasticity (White and Arch tests), and normality of residuals (Jarque-Bera and Shapiro-Wilk tests). When one of the tests converges toward the assumption of autocorrelation or heteroscedasticity, we use the White heteroscedasticity-consistent standard errors and covariance matrix in order to obtain robust standard errors. The stability of the econometric coefficients across time is also checked by performing the CUSUM test and the CUSUM squared tests.

2.3 Testing for Granger causality

The last part or our work consists in studying the temporal causality between US energy expenditure (as a fraction of GDP) and US GDP growth rates between 1960 and 2010. There are many causality tests based on different definitions of causality, but the main idea of the Granger (1969) causality test is to verify that adding past data of variable X_1 to past data of variable Y enhances the prediction of present values of variable Y. If the residuals generated from a model with variable Y and its past only, and from another model with the past of variable Y and the past of variable X_1 are significantly different, we can reject the assumption of non-causality from X_1 to Y and accept the assumption of a causality running from X_1 to Y. Formally, it consists in running the following Wald test:

$$H_0: \forall\, i \in [1, \dots, k], \theta_{1,i} = 0 \;and\; H_1: \exists\, i \in [1, \dots, k], \theta_{1,i} \neq 0,$$

$$Y_t = c + \sum_{i=1}^{i=k} \delta_i Y_{t-i} + \sum_{i=1}^{i=k} \theta_{1,i} X_{1,t-i} + \sum_{i=1}^{i=k} \theta_{2,i} X_{2,t-i} + \sum_{i=1}^{i=k} \theta_{3,i} X_{3,t-i} + \varepsilon_t. \tag{12}$$

[9] The correlogram of residuals is also checked in order to detect higher order of autocorrelation.

We also test the assumption that all the X_j variables are not Granger causing the variable Y by testing $H_0: \forall\ i \in [1, \dots, k], \theta_{1,i} = \theta_{2,i} = \theta_{3,i} = 0$, and $H_1: \exists\ i \in [1, \dots, k] \cup j \in [1, \dots, 3],\ \theta_{j,i} \neq 0$.

3. Results

3.1 US and global energy expenditure from 1850 to 2012

US energy expenditure

In Figure 2a we compare three different estimates of US energy expenditure as a fraction of GDP from 1850 to 2012 (excluding or including wood as marketed energy, and including wood with the total proxy calculation). We also show in this figure the US estimation of King et al. (2015b). Figure 2b shows the decomposition of our first best estimate (including wood as marketed energy) by energy type. In Figure 3 we relate graphically our first best estimation of the US level of energy expenditure (as a fraction of GDP) to the GDP growth rate from 1951 to 2010.

Quite logically, in early industrial times the US level of energy expenditure was low for fossil energy (coal, oil, and gas) and non-fossil electricity. In 1850 woodfuel expenditure still represented 14% of the US GDP when the overall energy expenditure level was 16%. The low price of coal (cf. Figure 1) explains that total energy expenditure decreased from 1850 (16%) to the 1900s (8%) despite a huge increase in consumption. From 1910 to 1945, total energy expenditure was about 14% of GDP because of ever-increasing (cheap) coal use and the newly increasing consumption of (expensive) hydroelectricity. From 1945 to 1973, which was the period of highest economic growth rates for the US and all other industrialized economies, the level of energy expenditure steadily declined from about 8% to 4%. In 1974 US energy expenditure surged to 10% of GDP, and in 1979 it reached 14.5%. These well-known periods, respectively called the first and second oil crisis, pushed industrialized economies into major recessions. After the beginning of the 1980s, the level of US energy expenditure decreased and reached a minimum of 4.2% in 1998. Then, US energy expenditure rose again (mainly because of the oil price) and reached 7.8% in 2008. After a fall to 5.7% in 2009, US energy expenditure remained around 7% from 2010 to 2012.

Figure 2a shows that including traditional biomass energy with the total proxy calculation yields a “second best” estimation of total US energy expenditure that is quite consistent with the “first best” estimation that includes wood as marketed energy. Hence, for a given country for which woodfuel prices are not available, the proxy calculation allows an adequate estimation of the order of magnitude of the total energy expenditure level. Similarly, if consumed quantity estimations of fodder and traditional windmills and water wheels were available without knowing their respective prices, the proxy calculation would be adequate to estimate the actual total level of energy expenditure.

Figure 3 indicates that some economic growth recessions are clearly preceded by surges in energy expenditure, and so the importance of energy in such a context cannot be ignored. This is obviously the case for the two oil crisis of the 1970s. On the other hand, the underlying energy basis is harder to discern for some economic recessions. In 1953, for instance, bad monetary policy decisions triggered a demand-driven recession in 1954. In the same way, the 1958 “Eisenhower recession” caused by depressed sales of cars and houses and high interest rates seems disconnected from any energy base.

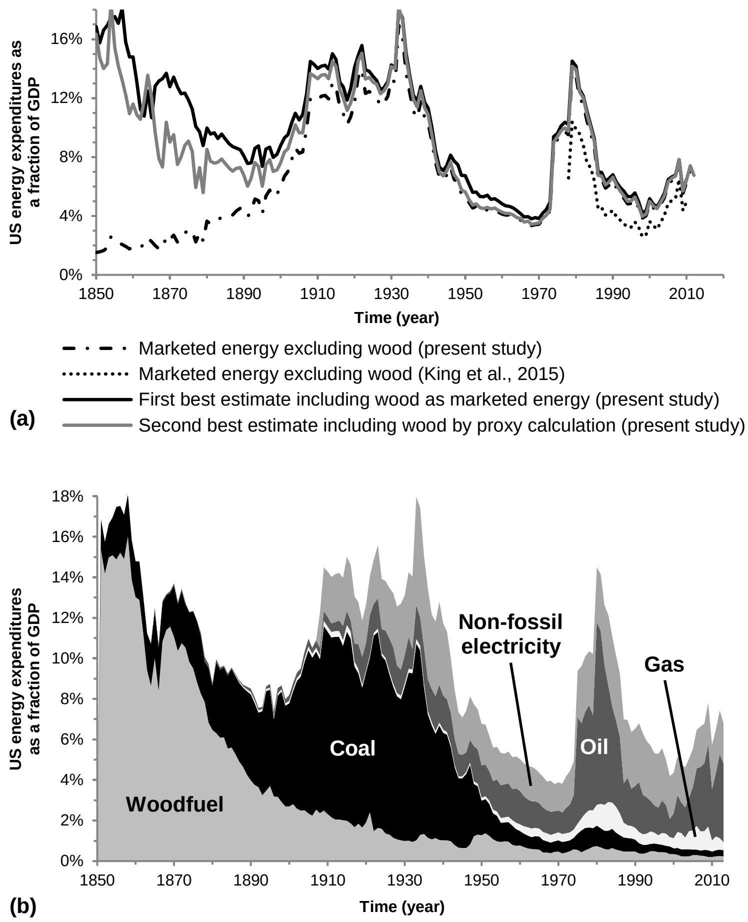

Figure 2. US energy expenditure estimates from 1850 to 2012. (a) Excluding wood as marketed energy as in King et al. (2015b) vs. including wood as marketed energy vs. total proxy calculation; (b) First best estimate decomposition by energy type.

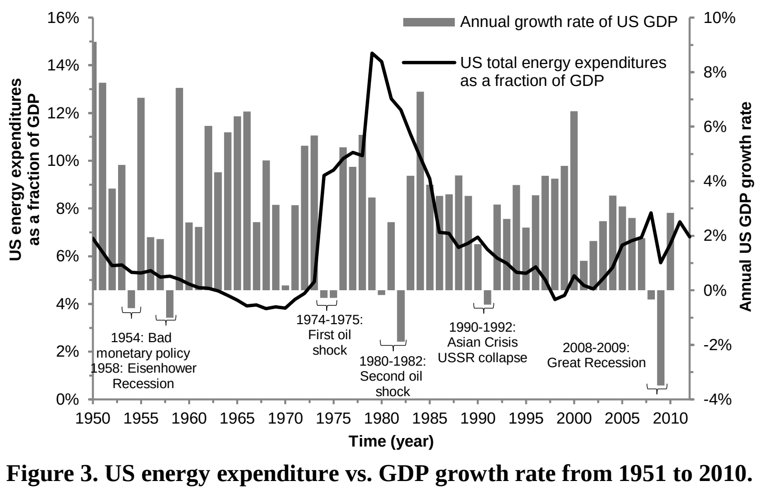

Figure 3. US energy expenditure vs. GDP growth rate from 1951 to 2010.

But other political and market-induced economic turmoil are in fact related to energy. For instance, though agonizing and crippled by multiple problems, the oil-exporting USSR probably collapsed in 1990, and not before, because low and ever decreasing oil prices in the early 1990s made its public budget untenable. Similarly, the bursting of the subprime bubble of 2007–2008, which initiated the Great Recession, was in place for a few years and was probably just waiting for a push that rocketing oil prices made visible.

Figure 3 is only meant to give qualitative intuitions about the energy-economic growth relation but upcoming results will support the main evidence of this article: energy is obviously not the only driver of economic growth but it is surely the most recurrent determinant of the economic process.

<u>Global energy expenditure</u>

Figure 4a shows our estimation of global energy expenditure as a fraction of GWP from 1850 to 2012 (excluding or including wood as marketed energy, and including wood with the total proxy calculation). This figure also shows the global estimation of King et al. (2015b). Figure 4b shows the decomposition by energy type of our global first best estimate including wood as marketed energy.

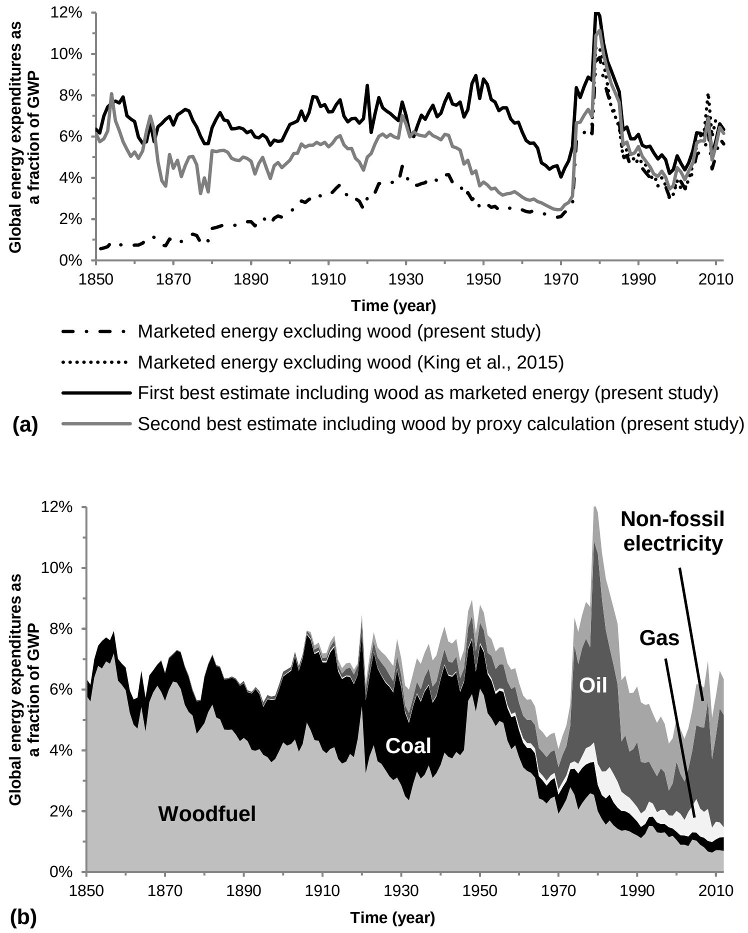

Figure 4. World energy expenditure estimates from 1850 to 2012. (a) Excluding wood as marketed energy as in King et al. (2015b) vs. including wood as marketed energy vs. total proxy calculation; (b) First best estimate decomposition by energy type.

World results confirm our analysis of the US energy-economy system. Periods of very high energy expenditure relative to GDP (from 1850 to 1945), or surges (in 1973–74 and 1978–79) are associated with low economic growth rates. On the contrary, periods of low or decreasing energy expenditure (from 1945 to 1973) are associated with high and increasing economic growth rates.

3.2 Maximum level of energy expenditure, maximum tolerable energy price, and minimum required EROI for the US economy

US economic growth regressions on energy expenditure, capital formation, and labor availability

Table 2 gives the results of the different ordinary least square regressions we have performed following equation (6) where US economic growth is the dependent variable and US energy expenditure, US capital formation, US population first difference, and US unemployment rate are the different explanatory variables.

Table 2. Results of multivariate regressions of US economic growth on energy expenditure, capital formation, and labor availability between 1960 and 2010.

	Dependent variable: US GDP growth rate				
Specification	**(I)**	**(II)**	**(III)**	**(IV)**	**(V)**
Constant	-0.180740 (0.045554)***	-0.260034 (0.052281)***	-0.277873 (0.052875)***	-0.276934 (0.053082)***	-0.264372 (0.057749)***
US oil expenditure	-0.406652 (-3.294917)***	-0.608737 (0.131068)***			
US fossil energy expenditure			-0.554234 (0.118643)***		
US total energy expenditure including wood				-0.475930 (0.114248)***	-0.522700 (0.152441)***
US capital investment	0.957723 (0.206976)***	1.206830 (0.205298)***	1.288255 (0.208538)***	1.307545 (0.208708)***	1.238985 (0.223166)***
US population first difference	-1.15E-09 (8.48E-10)				
US unemployment rate		0.434847 (0.252110)*	0.522721 (0.257490)**	0.605045 (0.284391)**	0.724169 (0.334816)**
dum1974					-0.018473 (0.004933)***
dum1979					0.011897 (0.010671)
dum1986					-0.017128 (0.006443)**
dum2009					-0.031794 (0.011243)***
R^2	0.493143	0.533416	0.540681	0.520744	0.583032
R^2 Adjusted	0.460790	0.503634	0.511362	0.490154	0.515154
Residual tests					
Durbin-Watson	1.683556	1.744475	1.765262	1.687059	1.623818
White	2.150983**	3.467135***	3.462751***	3.514716***	1.900220*
Arch (1)	0.170333	2.75E-05	0.025367	0.034475	0.006592
Jarque-Bera	0.686598	0.454564	0.305434	0.409832	4.152342
Shapiro-Wilk	0.986928	0.971674	0.972468	0.983263	0.968714
CUSUM test	Stability: yes	Stability: yes	Stability: yes	Stability: yes	/
CUSUM squared test	Stability: yes	Stability: yes	Stability: yes	Stability: yes	/

Note: Robust standard error estimates are reported in parentheses. * Significant at 10% level, ** 5% level, ***1% level.

In specification (I) we have considered only oil expenditure, capital investment, and US population. As suspected, population seems to be a poor proxy for labor as its effect is not statistically significant. To correct for this shortcoming, we introduce the US unemployment rate in all other specifications (II to V). Therefore specification (II) is similar to specification (I) except for the labor proxy. Specification (III) takes into account all three fossil energies (coal, oil, and gas), capital investment, and unemployment rate. In specification (IV) energy expenditure includes all fossil energies, non-fossil electricity and wood, whereas specification (V) is the same as (IV) with additional dummies to control for the impact of peculiar events, namely the two oil shocks (1974 and 1979), the oil counter-shock (1986), and the global Great Recession (2009).

We found a statistically significant (most of the time at 1% level) decreasing relation between the US economic growth and the level of energy expenditure as a fraction of GDP between 1960 and 2010 for all specifications. Increasing energy expenditure as a fraction of GDP is a sufficient condition for a decline in US economic growth but this factor is not a necessary condition for a contraction of the economy since geopolitical, institutional, socioeconomic, and climatic events, and the unavailability of capital and labor can also reduce economic growth. Specification (II) shows that an increase of one percentage point of oil expenditure is correlated to a 0.60 decrease in US economic growth. When all fossil fuel expenditure (III), or all energy expenditure (IV) are taken into account instead of just oil, energy expenditure still has a statistically significant negative impact on economic growth, but the correlation is slightly weaker. An increase of one percentage point of fossil (respectively total) energy expenditure is statistically correlated to a 0.55 (respectively 0.48) decline in US economic growth. As shown by specification (V), this result is robust to the inclusion of several dummy variables in order to control for the impact of particular events. Capital investment is always positively significant at 1% level. Each point of investment as a fraction of GDP raises economic growth by slightly more than one percentage point.

Surprisingly, the US unemployment rate is positively correlated with economic growth when the impact of energy expenditure and capital investment is also taken into account. To check this result, we made a simple regression of US economic growth on the US unemployment rate and found the classic decreasing relationship. Moreover, when we perform univariate linear regressions of the unemployment rate on capital formation (as a fraction of GDP) and on energy expenditure (as a fraction of GDP), we find that the unemployment rate is positively correlated to energy expenditure (the higher the energy expenditure as a fraction of GDP, the higher the unemployment rate) and negatively correlated to capital investment (the higher the capital investment as a fraction of GDP, the lower the unemployment rate). These results indicate that the apparently strange positive correlation between economic growth and unemployment is not caused by a flaw in our data or methodology. The residual checks converge toward the assumption of normality of residuals and the absence of autocorrelation, although there is some evidence for the presence of heteroscedasticity, thus we use robust standard error. The CUSUM and CUSUM squared tests indicate that the estimated coefficients are stable overtime.

It is worth noting that performing the same multivariate linear regressions at the global scale yields very similar results, in particular the statistically significant negative correlation between energy expenditure and economic growth. We choose not to reproduce these results because the CUSUM and CUSUM squared tests indicate that the estimated coefficients are not stable overtime for this global approach.

<u>Maximum tolerable level of energy expenditure for the US economy</u>

Let us consider now the estimation of the maximum level of energy expenditure as a fraction of GDP, β_{total}, above which positive economic growth vanishes. Following equation (8), and replacing parameters $\alpha, \theta_1, \theta_{2,} \theta_3$ by the estimated values of specification (IV) (so respectively, -0.28, -0.48, 1.31, and 0.61), and the mean values of capital formation as a fraction of GDP (0.2244) and unemployment rate (0.0598), we find the central value of the maximum tolerable level of total energy expenditure:

$$\beta_{total} = \frac{0.28 - 1.31 \times 0.2244 - 0.61 \times 0.0598}{-0.48} = 0.11. \qquad (13)$$

Using a Wald test, we can provide a minimum and maximum β_{total} at 5% level. We find that $0.09 < \beta_{total} < 0.131$. This result means that, in the US, if the fraction of energy expenditure is higher than 11% of GDP (with a 95% confidence interval of [9%–13.1%]), economic growth is statistically lower than or equal to zero (all others variables being equal to their mean values). Using parameter values from specification (II), we can perform the same test for oil expenditure only and derived the maximum tolerable level of oil expenditure for the US economy, β_{oil}, which is equal to 6% (with a 95% confident interval of [4.6%–7.5%]). Our results support the qualitative suppositions advanced by Murphy and Hall (2011ab) and Lambert et al. (2014).

<u>Maximum tolerable quantity-weighted average price of energy and oil for the US economy</u>

As shown in equation (9), we can reformulate equation (13) in order to get the expression of the maximum price of aggregated energy, $P_{average\,max}$, and the maximum price of oil, $P_{oil\,max}$, above which US economic growth should statistically become negative. Obviously, both estimates are absolutely not static but time dependent since for any given year, they respectively depend on the current total energy intensity and the current oil intensity of the US economy:

$$P_{average\,max,t} = \frac{\beta_{total}}{\frac{E_{total\,marketed,t}}{GDP_t}} = \frac{0.11}{\frac{E_{total\,marketed,t}}{GDP_t}}, \qquad (14)$$

$$P_{oil\ max,t} = \frac{\beta_{oil}}{\frac{E_{oil,t}}{GDP_t}} = \frac{0.06}{\frac{E_{oil,t}}{GDP_t}}. \qquad (15)$$

Relation (15) describing the maximum tolerable price of oil as a function of the oil intensity of the economy is represented in Figure 5 for the US, and compared with the actual historical course of the oil price between 1960 and 2012. We could have easily drawn this figure for total aggregated energy but, given the importance of oil for the US economy, we think that focusing on the oil price is more advisable here. If we consider the last data point of the econometric estimation we have for year 2010, Figure 5 indicates that the price of oil would have had to reach 16977 \$1990/TJ (equivalent to 173 \$2010 per barrel) instead of its real historical value of 8315 \$1990/TJ (84 \$2010 per barrel), to annihilate US economic growth. Figure 5 also shows that in 2008 the oil price was pretty close to the "limits to growth" zone, and one must not forget that average annual values are not representative of extremes and potentially lasting events. Oil prices increased continuously in the first half of 2008 reaching 149 \$2010 on July 11. This supports the idea that the surge in oil expenditure at this time indeed played a "limits to growth" role in lowering discretionary consumption and hence revealing the insolvency of numerous US households. A preliminary additional mechanism is to consider that instabilities on the financial market in 2007 led numerous non-commercial agents to take positions on apparently more reliable primary commodities markets (Hache and Lantz, 2013). This move inevitably puts upward pressure on prices, and in particular the oil price, which increased energy expenditure as a fraction of GDP to the point of triggering a "limit to growth" effect. Similarly, from 1979 to 1982, the actual oil price was above or slightly below its maximum tolerable value, which explains that US economic growth had very little chance of being positive during those years. On the contrary, at the time of the oil counter-shock of the late 1980s, the oil price was four times below its maximum tolerable level, so that the oil expenditure constraint was very loose at this time.

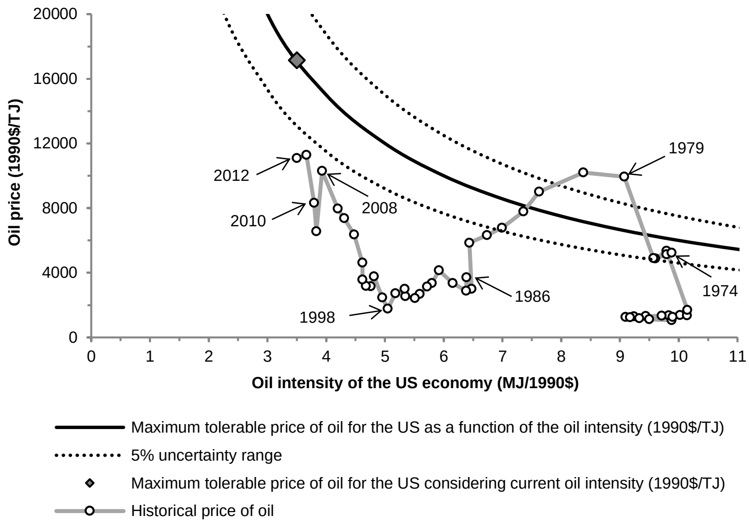

Figure 5. Maximum tolerable price of oil ($1990/TJ) for the US as a function of the economy's oil intensity.

<u>Minimum EROI required for having positive economic growth in the US</u>

As can be seen in equation (11), two variables are needed to calculate the minimum aggregated EROI, $EROI_{min}$, required for having positive economic growth in the US: the maximum tolerable level of energy expenditure β_{total} previously calculated, and the average monetary-return-on-investment (MROI) of the energy sector. In Court and Fizaine (2016) such average MROI of the US energy sector is estimated between 1850 and 2012 with an average value of 1.158 (meaning that on average the gross margin of the US energy sector has been about 15.8%, with a standard deviation of 2%). Using this average value of 1.158 for the MROI, and the value of 0.11 previously calculated for β_{total}, we estimate that the US economy requires a primary energy system with an $EROI_{min}$ of 11:1 in order to enjoy a positive rate of growth. Taking the uncertainty range (at 5% level) of β_{total} ([0.09–0.131]), and considering an MROI varying between 1.05 and 1.2, the sensitivity of the $EROI_{min}$ ranges from 8:1 to 13.5:1.

To the best of our knowledge, there are only three studies that discuss potential values for minimum societal EROI. Hall et al. (2009) offer a technical minimum EROI of 3:1 for oil at the well-head. These authors postulate (without explicit calculation) that a higher value of 5:1 would be necessary to just support our current complex societies, but that a minimum EROI around 12–14:1 is probably necessary to sustain modern forms of culture and leisure. Weißbach et al. (2013) give a minimum required EROI of 7:1 for OECD countries without a clear explanation of the underlying calculation. Finally, the study by Lambert et al. (2014), based on simple (although nonlinear) correlations between EROI and the Human Development Index (HDI) in cross sectional data, arrive at a minimum required societal EROI in the range 15–25:1 for contemporary human societies.[10]

Now that we have estimated that, at current energy intensity, the US requires a minimum societal EROI of 11:1 (with a most likely interval[11] of [8–13.5]) in order to possibly

[10] In their study Lambert et al. (2014) define a minimum EROI in order to reach a minimum HDI which is quite different from our minimum EROI below which positive economic growth is statistically compromised.

[11] This expression is used because it is impossible to formally define a 5% or 10% confidence interval for the $EROI_{min}$. Indeed, such confidence interval is known for β_{total}, but not for the MROI for which only a standard deviation of 2% is known. Hence,

have positive economic growth, the temptation is to compare this value to the representative EROI of different energy systems in order to assess their "growth-compatibility". Such comparison appears rather perilous. First, studies proposing EROI values sometimes calculate ratios of annual gross energy produced to annual energy invested which hence represent power return ratios (PRRs), or "yearly" energy return ratios (ERRs) comparable to our $EROI_{min}$; but more formally, EROIs should describe ratios of cumulated energy production to total energy invested, and such estimates can be found in the literature too. Second, there is no such thing as an "average representative EROI value" for a given energy system. Each energy system has a particular EROI that depends on the considered input boundary (see Murphy et al, 2011). The bottom line is that orders of magnitude of net energy ratios (be it ERRs or PRRs) are important, precise calculated values are not. Hence, the different numbers given here must absolutely be understood as representative orders of magnitude. Coal, oil, and gas have respective representative EROI values of about 80–100:1, 20–30:1, and 40–60:1. Hydropower projects have high EROIs of about 50–100:1 (but the global remaining hydro potential will probably come to saturation in a few decades). New renewable technologies toward which human future is destined have relatively lower EROIs, with average values for wind power, photovoltaic panels, and first generation biofuels respectively around 15–20:1, 4–6:1, and 1–2:1 (Hall et al., 2014). Adding the intermittent nature of renewable energy to this perspective suggests that (so far) new renewable technologies hardly seem capable of coping with the minimum required societal EROI of 11:1 that we have calculated.

For the sake of clarity, Table 3 summarizes different scattered results of this subsection 3.2.

Table 3. β, P_{max}, and $EROI_{min}$ using parameter values from specification (IV) and (II)

	US total energy expenditure including wood (IV)	US oil expenditure (II)
β (%)		
Max 5%	13.1%	7.5%
Average	11%	6.0%
Min 5%	9%	4.6%
P_{max} ($1990/TJ)		
Max 5%	12023	21347
Average	10096	16977
Min 5%	8260	12921
$EROI_{min}$		
Max 5%	13	25
Average	11	19
Min 5%	9	15

Note: P_{max} estimates depend on the level of energy intensities taken here for year 2010, i.e. 10.9 MJ/$1990 for total energy and 3.8 MJ/$1990 for oil only.

the interval [8–13.5] was computed to simply get an idea of the sensitivity of the estimated average $EROI_{min}$ but this interval must surely not be taken as a formal result.

3.3 Granger causality relation between oil expenditure and US GDP growth rate between 1960 and 2010

Over the period 1960–2010 for which we have uninterrupted year-to-year data, we performed Granger causality tests to identify the direction of the possible causal relation between the US level of oil expenditure as a fraction of GDP, US capital formation as a fraction of GDP, US unemployment rate, and the growth rate of the US GDP. Our results, presented in Table 4, show that we can reject at 5% level the assumption that the level of oil expenditure as a fraction of GDP does not Granger cause economic growth. For the reverse relation, the assumption that growth does not Granger cause the level of oil expenditure (as a fraction of GDP) cannot be rejected at 5% level. In summary, these tests indicate a one way causality from energy expenditure to economic growth at 5% level. Applying the same methodology, we also find a one way causality running from the US level of oil expenditure to the US unemployment rate (Figure 6). Finally, the Granger causality test also tends to confirm a feedback relationship between the US economic growth and the US unemployment rate at 5% level. Furthermore, contrary to our static econometric results (Table 2), the impulse response functions estimated from the vector autoregression (VAR) used in Granger causality tests show in a dynamic way how a variable can be impacted by a modification of another variable. We found that an increase in energy expenditure (as a fraction of GDP) in a given year leads to an increase in the unemployment rate two years later and a decrease in economic growth in the three years following the initial rise in energy expenditure. Quite logically, we observed also that economic growth reacts negatively to a rise in the unemployment rate and positively to a rise in capital investment (as a fraction of GDP).

It is worth adding that using total energy expenditure instead of oil expenditure in the same Granger causality tests yields identical results. However, with those data, autocorrelation problems could only be solved by increasing the number of lags in our relations. Considering the low number of observations that we have, this strategy reduces the robustness of these results and we consequently choose not to reproduce them here.

Table 4. Results of Granger causality tests with different US variables.

Dependent variable	**Sources of causation (independent variables) with 1 lag**				
	Oil expenditure	GDP growth	Unemployment rate	Capital formation	All
Oil expenditure	-	2.321782	0.278008	0.514794	3.049061
GDP growth	11.61990***	-	19.58885***	1.083957	25.73877***
Unemployment rate	10.22715***	10.69602***	-	0.100274	46.42257***
Capital formation	1.243340	6.466733**	9.453183***	-	21.49198***

Note: To determine the lag order, we used the lag order chosen by the majority of information criteria (in our case 4 out of 5 information criteria indicated an optimal order of one lag). We also checked that the VAR is well specified and that there was no persistent autocorrelation. *corresponds to the F-statistic result of the Fisher test rejecting the assumption H_0: "the variable X_i does not Granger cause the variable Y" with a 10% risk level, ** 5% risk level, *** 1% risk level.

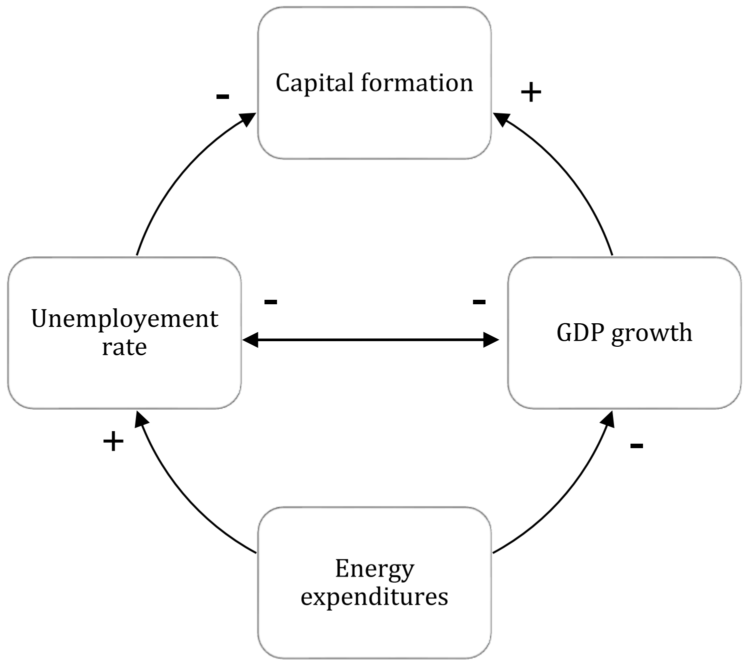

Figure 6. Relationships highlighted by our VAR regression for the US economy between 1960 and 2010.

Let us summarize the results obtained so far in this paper on the "limits to growth" role of energy expenditure. (i) The level of energy expenditure in the economy, i.e. the amount of GDP diverted to obtain energy, seems to play a "limit to growth" role since as long as it has remained above 6–8% of GDP, high economic growth rates have never occurred for the US or the global economy during the last one hundred and fifty years. (ii) A statistically significant negative Granger causality was found from the US level of oil expenditure towards US GDP growth between 1960 and 2010. (iii) If the rate of growth of the economy is to be potentially positive (in the absence of other major limits of geographical, geopolitical or institutional nature), energy expenditure cannot exceed a certain fraction of GDP that we have estimated to be 11% for the US. (iv) This result can also be expressed as the necessity of having an energy system with a definable minimum EROI, estimated at 11:1 for the US. In the following section, we discuss some of these results.

4. Discussion

4.1 Consistency and comments about our long term energy expenditure estimations

<u>Comparison with the UK on a larger time frame</u>

Relying on the methodology presented in section 2.1 we have estimated the level of primary energy expenditure for the UK, for which Fouquet (2008, 2011, 2014) has provided a lot of very long-term (1300–2008) data and analyses. More specifically, the prices (£2000/toe[12]) and quantities (Mtoe) of coal, oil, gas, electricity, wood, and fodder consumed in the UK were retrieved from Fouquet (2008) for the period 1300–1699, and we used updated values from Fouquet (2011, 2014) for the period 1700–2008. UK GDP (£2000) was retrieved from Fouquet (2008). As our results in Figure 7 show, when energy expenditure is calculated as far back as 1300, ignoring expenditure related to food (supplied to laborers to obtain power) and fodder (provided to draft animals to obtain power) could lead to a huge underestimation of the past energy cost burden. Indeed, getting total non-human-food energy (but including

[12] 1 toe = 1 tonne of oil equivalent = 42 GJ.

fodder indispensable to obtain draft animals' power) used to account for 30–40% of the economic product of the UK in the late Middle Ages, and adding human food energy (indispensable to obtain power from laborers) increases such an estimate to 50–70% for the same early times. Even in 1700, food supplied to laborers, wind used for ships and mills, and fodder provided to draft animals accounted for nearly 45% of the total primary energy supply of the UK, and still represented 20% in 1850 (Fouquet, 2010). Nevertheless, Figure 7 shows that, compared to the US and the global economy (Figures 2 and 4 respectively), the energy transition of the UK toward fossil fuels was far more advanced in 1850. At that particular time, coal expenditure was about 9.5% of GDP in the UK, but only 2% in the US, and 1.5% at the global scale. Furthermore, ignoring food and fodder as we did for the US and the global economy, the relatively low level of "fossil + woodfuel" energy expenditure of the UK between 1700 and 1800 is, to our mind, a clear sign of the decisive role played by cheap coal to give the UK a head start over other nations in the Industrial Revolution that ultimately lead to the Great Divergence among well-off western and less-developed eastern countries (see Pomeranz, 2000; Kander et al., 2013; and Wrigley, 2016).

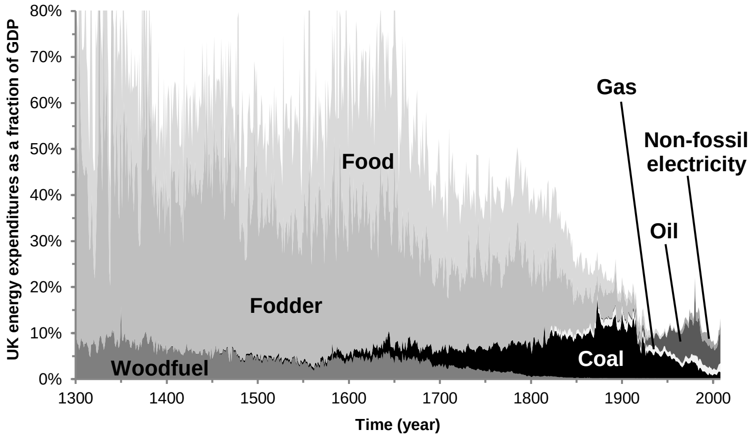

Figure 7. UK energy expenditure estimates from 1300 to 2008 with decomposition by energy type.

Sensitivity analysis of the US energy expenditure to the GDP data

In Figure 8 we test the sensitivity of the US total energy expenditure to the choice of the GDP estimate. As could have been expected, our total energy expenditure estimates are consistent after 1950 since international accounting rules have only been established after the Second World War. Before 1950, nominal GDP estimates and deflator estimates vary more widely among authors but it does not generate too important differences in our energy expenditure estimates.

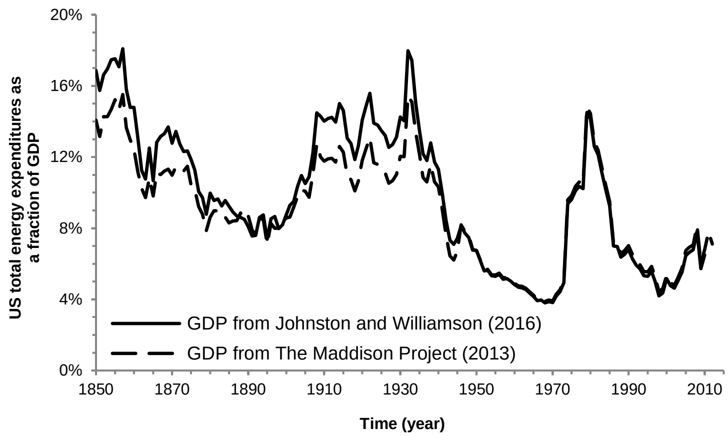

Figure 8. Sensitivity analysis of US total energy expenditure to the GDP estimate source

Consistency with Bashmakov's "first law"

According to our results, it seems that the "first energy transition law" postulated by Bashmakov (2007) concerning the stability of energy costs to income ratios ("with just a limited sustainable fluctuation range") is valid for the post-Second World War era but not for earlier periods. On the whole, our results suggest that the ratio of US energy expenditure to GDP has decreased from an average value of 11% for the period 1850–1950 to a lower average value of 5.7% for 1950–2012. The fact that Bashmakov's "first law" does not hold in the very long-term is even more visible if we observe the energy requirements of the UK between 1300 and 2008, as we did in Figure 7.

4.2 Extension of econometric results: per capita GDP and threshold effects

Regarding the diverse econometric regressions performed in this paper, an alternative approach might be to analyze the relationship between energy expenditure (as a fraction of GDP) and the growth rate of per capita GDP instead of total GDP as we did. We tested this option and found similar outcomes. We deliberately choose to focus our study on GDP growth and not per capita GDP growth in order to remain consistent with the existing literature.

We could also suppose the existence of thresholds effects in the relationship between economic growth and energy expenditure (as a fraction of GDP) instead of the linear relationship assumed in this paper. This assumption is a key point of Bashmakov's work (2007). Whether this relationship is linear or not (threshold existence) involves the presence or absence of trade-offs between high energy expenditure as a fraction of GDP (causing high effort of energy efficiency) and high economic growth. Unfortunately, considering the restricted number of observations (fewer than ten) that we have for high levels of energy expenditure, it remains quite complicated to derive robust econometric estimations for such high regimes. The use of panel data could be a good way to overcome this technical barrier, and this option might be explored in further work.

Furthermore, we think other parts of our work should be replicated for other countries, especially developing ones. Developing countries should be in a position to devote more expenditure to energy (as a fraction of their GDP) due to the higher energy intensity of their economies, so indicating a higher β_{total} and a lower $EROI_{min}$ for those countries. This point remains to be confirmed.

5. Conclusions and policy implications

In this article we estimated the level of energy expenditure from 1850 to 2012 for the US and the global economy, and from 1300 to 2008 for the UK. Our results indicate that periods of high or suddenly increasing energy expenditure levels are associated with low economic growth rates: for instance from 1850 to 1945 (very high energy expenditure levels), from 1975 to 1976 (surge), and from 1981 to 1983 (surge). On the contrary, periods of low and decreasing energy expenditure are associated with high and increasing economic growth rates: for instance from 1945 to 1973, and in the early 2000s. Over the more restricted period 1960–2010 for which we have continuous year-to-year data for the US, we performed several Granger causality tests that consistently show a one way temporal causality running from the level of energy expenditure (as a fraction of GDP) to economic growth. Furthermore, we were able to show that in order to have a positive growth rate, from a statistical point of view, the US economy cannot afford to allocate more than 11% of its GDP to primary energy expenditure. This means that considering its current energy intensity, the US economy needs to have at least a societal $EROI_{min}$ of approximately 11:1 (that conversely corresponds to a maximum tolerable average price of energy of twice the current level) in order to present positive rates of growth.

Our results suggest two main facts. (i) Energy is crucial for economic growth, which tends to reinforce the conclusion drawn by the biophysical movement and weakens the mainstream position which sees energy as a common (if not minor) factor of production. (ii) If we take the societal EROI as an indicator of economic sustainability, it must be prevented at all costs from falling below its minimum threshold (estimated around 11:1 for the US). Such a decrease in societal EROI may arise in three different ways. First, it could arise from large fall in the energy production level, this is the position supported by the proponents of the peak oil theory. Second, the fall of the societal EROI could also occur because of increased energy investment levels (and associated increases in energy prices) in the different energy sectors due to the decreasing accessibility of energy (this is typically happening when the proportions of lower quality fuels such as shale oil and tar sands increase in the primary energy supply mix). Finally, the decrease in societal EROI could come from a combination of the two previous possibilities. Hence, like many before us, we recommend that a coherent economic policy should first be based on an energy policy consisting in improving the net energy efficiency of the economy. A "double dividend" would be associated to this type of measure because it would both increase the societal EROI (through a decrease in the energy intensity of capital investments) and decrease the sensitivity of the economy to energy prices volatility. This recommendation is supported by the crucial role played by energy efficiency both, in the level of energy expenditure spent as a fraction of GDP and in the determination of the societal EROI.

After the two oil shocks, economic agents largely switched toward technologies that consume less energy, leading to a global fall in energy intensity (compared with the 1950s and 1960s). This effort has enabled most industrialized economies to overcome the impact of higher energy prices on economic growth, while it has also increased the societal EROI of many economies. Two important questions remain. First, can new public policies adequately increase the energy efficiency of the economy even in low energy price periods? This would be needed in order to prevent the impact of future energy shocks on the economy, which can occur for several reasons: the depletion of cheap and accessible fossil fuels, the adoption of a global CO_2 price, or the decreasing availability of strategic raw materials that are of critical importance for so-called clean energy technologies. Of course, the energy rebound effect would have to be mitigated if we want to maximize the benefits of such a policy, which, historically, seems to be rather difficult (Sorrell, 2009). Second, previous studies related to the determinants of energy intensity concentrated mostly on the decreasing dynamics of this variable. Implicit in this view is the idea of a possible infinite relative decoupling of GDP from energy. As we are personally convinced that macroeconomic energy intensities cannot decrease asymptotically towards 0 MJ/$ due to the law of thermodynamics, a promising avenue of research could be to identify this minimum level and when we are likely to reach it.

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Appendix

Tableau A1. Unit root tests for the different time series used in econometric tests.

	Augmented Dickey Fuller H0: Unit root			**KPSS H0: Stationarity**	
	Constant +trend	Constant	None	Constant	Constant +trend
1960-2010					
US oil expenditure (as a fraction of GDP)	-1.822384	-1.844912	-0.870011	0.122781	0.125029*
US fossil expenditure (as a fraction of GDP)	-1.687235	-1.710704	-0.674999	0.126273	0.127640*
US total expenditure excluding wood (as a fraction of GDP)	-1.465321	-1.514866	-0.338669	0.144865	0.145643*
US total expenditure including wood (as a fraction of GDP)	-1.427043	-1.463141	-0.356135	0.144510	0.146239**
1960-2010 + dummies for 1974 and 1979					
US oil expenditure (as a fraction of GDP)	-4.645914***	-4.569183***	-3.968411***		
US fossil expenditure (as a fraction of GDP)	-3.855898**	-3.839113***	-3.216946***		
US total expenditure excluding wood (as a fraction of GDP)	-3.391457*	-3.332861**	-2.655416***		
US total expenditure including wood (as a fraction of GDP)	-3.374901*	-3.349661**	-2.697435**		
1980-2010					
US oil expenditure (as a fraction of GDP)	-2.544073	-4.054355***	-3.577915***	0.318747	0.185862**
US fossil expenditure (as a fraction of GDP)	-2.141382	-3.517222**	-3.084142	0.339279	0.185632**
US total expenditure excluding wood (as a fraction of GDP)	-1.664036	-3.305788**	-2.801680***	0.428181*	0.185309**
US total expenditure including wood (as a fraction of GDP)	-1.691725	-3.403323**	-2.912801***	0.448936*	0.184505**
1960-2010					
US population	-0.491776	1.621706	18.19552	0.954076***	0.218951***
US population first difference	-6.618667***	-6.349020***	-0.839929	0.383025*	0.108030
US unemployment rate	-2.987014	-2.977318**	0.019169	0.140524	0.124060*
US capital formation (as a fraction of GDP)	-2.784603	-2.201140	-0.637669	0.435677*	0.070891
US capital formation (as a fraction of GDP) + dummy in 2009	-1.402460	-3.106758**	-0.292106		
U S GDP growth rate	-5.761052***	-5.535544***	-3.757663***	0.284838	0.077606

Note: * Significant at 10% level, ** 5% level, ***1% level.

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